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Force direction and physical load in dynamic pushing and pulling

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In pushing and pulling wheeled carts, the direction of force exertion may, beside the force magnitude, considerably affect musculoskeletal loading. This paper describes how force direction changes as handle height and force level change, and the effects this has on the loads on the shoulder and low back. Eight subjects pushed against or pulled on a stationary bar or movable cart at various handle heights and horizontal force levels while walking on a treadmill. The forces at the hands in the vertical and horizontal direction were measured by a force-transducer. The forces, body movements and anthropometric data were used to calculate the net joint torques in the sagittal plane in the shoulder and the lumbo-sacral joint. The magnitudes and directions of forces did not differ between the cart and the bar pushing and pulling. Force direction was affected by the horizontal force level and handle height. As handle height and horizontal force level increased, the pushing force direction changed from 45° (SD 3.3°) downward to near horizontal, while the pulling force direction changed from pulling upward by 14° (SD 15.3°) to near horizontal. As a result, it was found that across conditions the changes in force exertion were frequently reflected in changes in shoulder torque and low back torque although of a much smaller magnitude. Therefore, an accurate evaluation of musculoskeletal loads in pushing and pulling requires, besides a knowledge of the force magnitude, knowledge of the direction of force exertion with respect to the body.

1. Introduction

The activities of lifting or carrying are generally assumed to be related to low back injury. Therefore, lifting and carrying tasks are being replaced by pushing and pulling tasks in many work places (Schibye *et al*. 1997). However, the physical load in pushing and pulling may also lead to health complaints. In a review Hoozemans *et al*. (1998) concluded from various epidemiological studies that 9–18% of low back injuries are associated with pushing and pulling. An increased risk of shoulder complaints for regularly pushing and pulling of wheeled cages has been reported by van der Beek *et al*. (1993).

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Factors affecting the low back and shoulder load, in pushing and pulling wheeled objects, are the magnitudes and directions of the exerted hand forces. In fact, the effects of the force magnitudes on musculoskeletal loads depend on the force directions with respect to the body. In biomechanical terms, the product of force magnitude and its moment arm length with respect to a joint affects the net joint moment, which is closely related to the required muscle forces at a joint and the resultant joint loading forces.

Despite its importance, the direction of force exertion in pushing or pulling receives little attention in the ergonomics literature. Yet, this direction is not obvious. Various studies on static pushing against and pulling on a stationary bar showed that those who are asked to generate a maximal horizontal force prefer to exert a force with an angular deviation from the horizontal (Warwick *et al*. 1980, Grieve and Pheasant 1981, Pinder *et al*. 1995). In the act of pushing a wheelchair while walking, at horizontal force levels of 10 and 40 N and various handle heights, the force was directed so that its reactive force was pointing towards the shoulder (Abel and Frank 1991).

Several principles underlie the direction of force exertion in pushing and pulling. First, the force direction is bound to constraints to preserve balance and to prevent a person from slipping. For balance, the torque due to the gravity vector on a person's body, with respect to the point of application of the ground reaction force, should be opposite and equal to the torque (with respect to the same point) due to the exerted hand force. To prevent slipping, the horizontal component of the exerted force is limited to the maximum friction force at the feet. Within these constraints, it seems mechanically and energetically preferable to direct the exerted force in such a manner that net joint moments are kept small, implying low needs for muscular action. This agrees with the observation of the reactive hand force pointing towards the shoulder in pushing (Abel and Frank 1991), which minimizes the shoulder torque as well as the torque at low back level (where a backward torque due to the reactive hand force is neutralized by a forward torque due to gravity). In maximal static pushing and pulling where joint centres were brought in line with the hand reactive force, the principle of minimizing net joint moments is also perceptible (Pheasant and Grieve 1981).

For dynamic pushing and pulling at common force levels at work (e.g. 100 – 500 N), some questions remain to be solved. In particular, what is the direction of force under conditions of varying handle height and force level and how does it affect the musculoskeletal shoulder and low back load? To answer these questions the direction of force exertion and the net joint moments in the shoulder and the lumbosacral (L5/S1) joint were studied in subjects who were pushing and pulling at various handle heights and force levels while walking on a treadmill. Similarly to previous studies (Kemper *et al*. 1990, Snook and Ciriello 1991, Mital *et al*. 1993), our subjects pushed against or pulled on a stationary horizontal bar fixed above the treadmill. To determine whether this bar pushing or pulling is comparable with the pushing or pulling of a wheeled object, the subjects also moved a four-wheeled cart on the treadmill.

2. Methods

2.1. *Subjects and tasks*

Eight male subjects — mean (SD) age 23.0 (2.3) years; mean stature 1.87 (0.06) m; mean total body mass 80.3 (7.6) kg — participated in the study after they had given their written informed consent.

The subjects performed pushing and pulling tasks while walking on a treadmill at a steady pace of 0.75 $m \cdot s^{-1}$ in pushing and 0.50 $m \cdot s^{-1}$ in pulling. In two sets of trials they pushed against and pulled on a stationary horizontal bar. In two other sets they pushed and pulled a four-wheeled cart on the treadmill. The paces for pushing and pulling were chosen after pilot trials as those considered normal and which could be performed comfortably by the subjects. For pulling when walking backwards, the normal and comfortable pace was somewhat lower than pushing while walking forward.

When using the bar, the exerted and target horizontal force were displayed graphically on a computer screen before the subjects. The subjects were instructed to adjust the exerted horizontal force to the target level in their own, most comfortable way. Nine conditions for pushing and nine for pulling were created by setting the target force to 15, 30 or 45% of each subject's total body mass and by adjusting the bar height to 60, 70 or 80% of the shoulder height in pushing and to 50, 60 or 70% of the shoulder height in pulling. By choosing the three target force levels, low, middle and high (near-maximal) intensity tasks were created. The various handle height levels were chosen such that the middle one reflected the optimal height, both for pushing and for pulling. The optimal heights were chosen on the basis of data published in the literature, as those at which the maximum force could be delivered (Ayoub and McDaniel 1974) and the maximum acceptable weights could be handled (Snook and Ciriello 1991, Mital *et al*. 1993).

When using the cart, the subjects pushed against or pulled on the same horizontal bar now attached to the cart. The cart weighed 135 kg. The rolling resistance was 50 N. The two wheels nearest to the subject could swivel. The subjects were instructed to move the cart in their most comfortable way. The required horizontal force to push and pull the cart was adjusted to a level of 15 or 45% of the total body mass by using weights attached to the cart via a rope and pulley mechanism (figure 1). The bar height was adjusted to 50 or 70% of the shoulder height. This resulted in four cart pulling and four cart pushing conditions.

In bar and cart pushing and pulling, the subjects were exposed twice to each condition of force level and handle height, but never in two successive trials. Varying the order of the sets and the order of trials within each set systematically varied the order of the trials. Before the trials, the subjects were familiarized with their tasks.

2.2. *Measurements*

A video-based motion analysis system (VICON, Oxford Metrics) was used to determine the positions in the sagittal plane of light-reflective markers attached to the horizontal bar and to the skin on the head (just in front of the bitragion), the spinous process of the first thoracic vertebra, and the wrist, elbow, shoulder, ankle and the lumbo-sacral (L5/S1) joint centres. To measure the instantaneous force exertion in the vertical and horizontal directions in the sagittal plane, the bar was equipped with a force transducer based on strain gauges. The measured force was the sum of the forces applied by the two hands. The force signals and movement data were stored on computer at a sample frequency of 60 Hz. Before each measurement, the subjects performed the task until they felt comfortable and steady. The measurement then started after a signal from the subject and it lasted five step cycles.

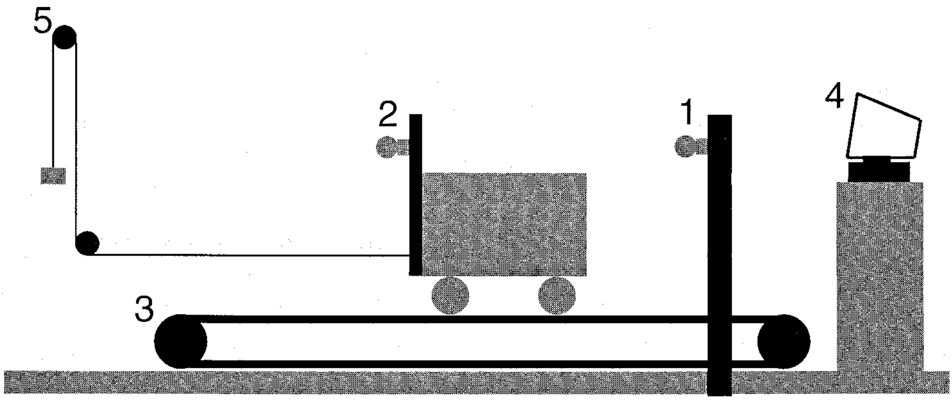

Figure 1. Experimental set up. Subjects pushed against and pulled on a horizontal bar that was either in a stationary position (1) or attached to a cart (2), while they were walking on the treadmill (3). When using the stationary bar, subjects were instructed to exert a horizontal force equal to the target force, both presented on a computer screen (4). When pushing and pulling the cart, the various horizontal force levels were set by using a pulley-mechanism (5).

2.3. *Data analysis*

For each trial, the data obtained in the middle three of the five consecutive step cycles, which were determined on the basis of the recorded ankle position, were further analysed. From the horizontal and vertical force signals the direction of its resultant total pushing or pulling force was computed. The marker positions were low-pass filtered at a cut-off frequency of 5 Hz (second-order Butterworth). By double differentiation of the filtered positions, linear and angular accelerations of body segments representing the hands, lower arms, upper arms, head and trunk segments were calculated.

The horizontally and vertically exerted forces, both the kinematic and anthropometric data were input into a two-dimensional linked segment model that calculated the net joint moments in the shoulder and L5/S1 joint by inverse dynamics (de Looze *et al*. 1992). The variation over time of the force signals and net joint torques was examined before calculating the averages of force and torque over the total duration of over three consecutive step cycles. Further statistical analysis was performed on values averaged over time.

2.4. *Statistics*

Test–retest differences (between the first and second trial of each condition) in force magnitude and direction were studied in an analysis of variance with repeated measures. Test – retest correlations across conditions were studied using Pearson's coefficient of correlation. Analyses of variance with repeated measures were used to study the significance of the effects of the horizontal force level and handle height on the force direction and the net torques in the shoulder and L5/S1. Differences and correlations between stationary bar and cart conditions with respect to force direction and net joint moments were evaluated with an analysis of variance and Pearson's coefficient of correlation. All tests were performed at a significance level of 0.05.

3. Results

3.1. *Task performance*

In the trials with the stationary bar, the subjects were capable of exerting a horizontal force that was close to the target level. At the target level of 15% body weight, the exerted horizontal forces were on average (SD) only 8.2 (11.5) N higher than the target. At the 30 and 45% level, the exerted horizontal force (SD) was respectively 2.9 (12.7) and 10.4 (14.7) N lower than the target.

Figure 2 shows typical time curves of the magnitude and direction of force exertion. The force magnitude shows a variable temporal pattern coinciding with the step cycles. The force direction shows only minor variations in time. Angular deviations from the horizontal are apparent, both in the upward and downward directions. The two conditions of handle height and force level show clear differences in force direction. The bar and cart conditions show similar results.

The retests showed that the force magnitude and direction were highly reproducible. No significant test–retest differences were observed and the test–retest correlations across conditions were all significant and ranged between subjects from 0.85 to 0.98. In the following analysis the test–retest results were averaged.

3.2. *Force direction on the stationary bar*

Both in pushing and pulling, the direction of force exertion becomes more in line with the horizontal as horizontal force level and handle height increased (figure 3, table 1).

In pushing, the direction ranges from pushing downward at a mean (SD) angle with respect to the downward vertical of 45.6 (3.3)° at the lowest force level and handle height to pushing slightly upward at 96.1 (2.6)° at the highest force level and handle height. In pulling, the effects of force level and handle height were also significant but considerably smaller then pushing. Among conditions, the direction varied from pulling upwards at 256.0 (15.3)° at the lowest force level and handle height to pulling slightly downwards at 276.3 (6.1)° at the highest force level and handle height.

3.3. *Net joint torques at force exertion on the stationary bar*

Figures 4 and 5 show the net shoulder and low back torques at the L5/S1 joint for bar pushing and pulling.

The net joint torques in the shoulder were negative in pushing, i.e. the performance of the task would have the effect of rotating the arms backwards (if there were no counteracting muscle forces) and positive in pulling, i.e. the task would have the effect of rotating the arms forwards. In pushing the absolute shoulder torque was significantly and positively affected by handle height and horizontal force level. In pulling, the effect of horizontal force level was positively correlated and the effect of handle height was negatively correlated to the absolute shoulder torque. The effects of handle height on shoulder torque were generally much smaller than the effects of force level.

The net joint torques at low back level were all positive in pushing and all negative in pulling. which indicates that these tasks have a trunk extending and a trunk flexing effect (to be offset by the trunk muscles) respectively. The absolute L5/S1 torque values for pushing were much smaller than the absolute values for pulling (figure 5). In pushing, only the effect of the horizontal force on the net L5/S1 torque was significant, but it was small: a change in horizontal force for the lowest to the highest target level lead to an increasing L5/S1 torque from 42 to 62 Nm. In pulling, the net L5/S1 torque was negatively correlated to handle height and positively correlated to force level. A change of the handle from the lowest to highest height resulted in a decreasing trunk flexing torque from 129 to 62 Nm (averaged over the

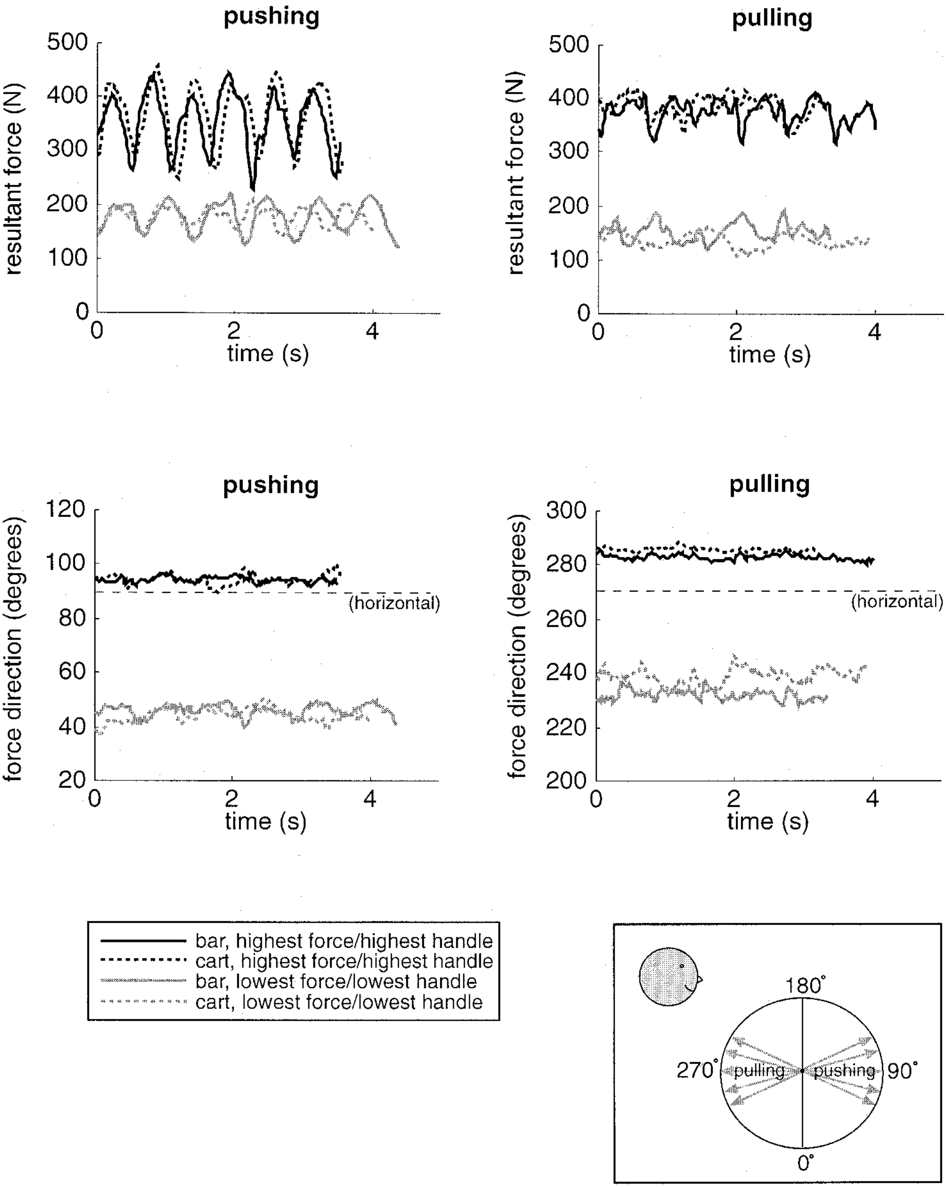

Figure 2. Time curves of the resultant force exertion and the force direction for one of the subjects during the course of three complete step cycles. Pushing against and pulling on the fixed bar and the cart are presented for the conditions of the highest and the lowest horizontal force target level and height handle. The direction of the pushing and pulling force was expressed in degrees, as illustrated in the right lower panel, showing also the position of the subject.

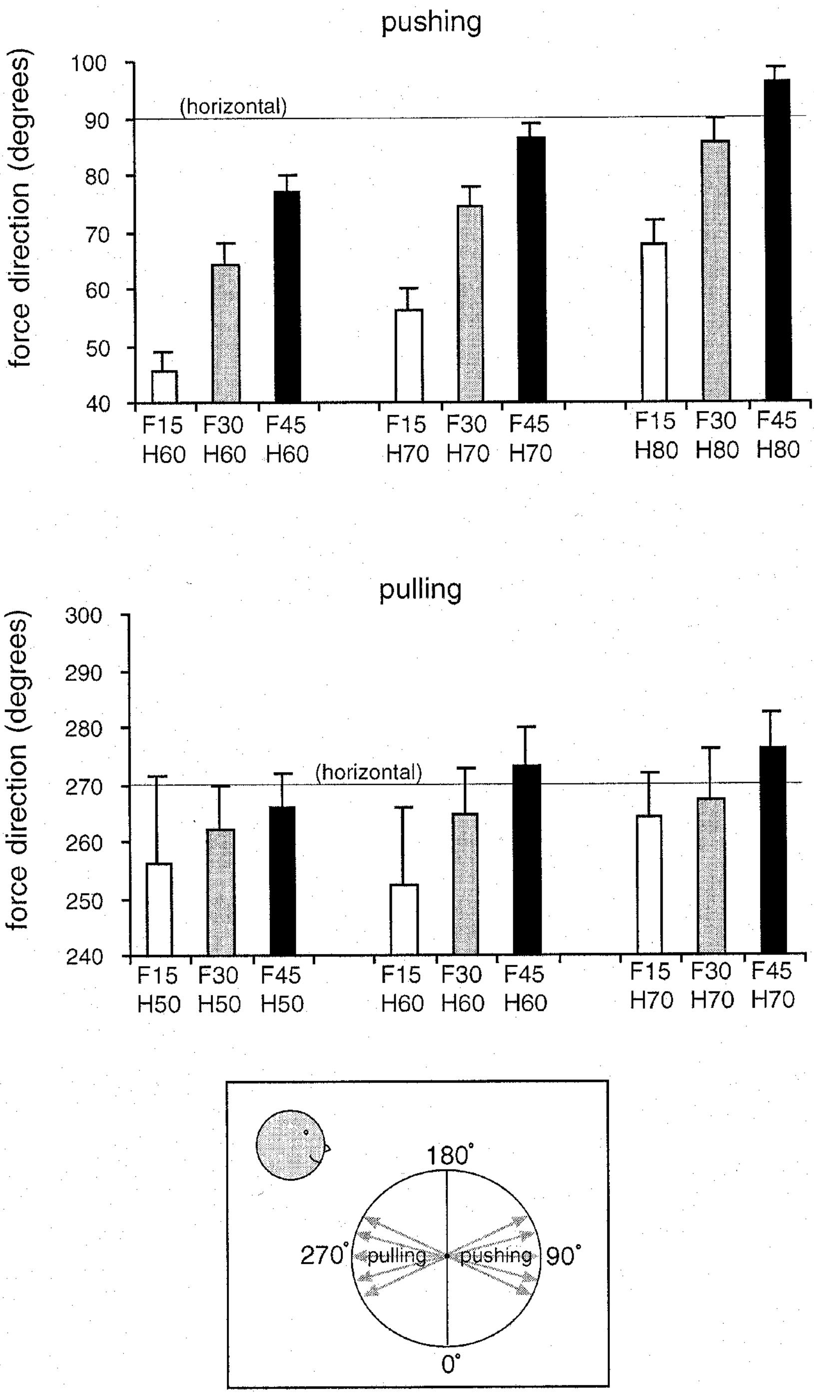

Figure 3. Means and SD of the force direction in terms of the angle of the exerted force vector relative to the downward vertical. The results presented are obtained from pushing against and pulling on the fixed bar in the various force level (F) and handle height (H) conditions.

Table 1. Results of analysis of variance with repeated measures. Significance of the effects of handle height (H) and horizontal force level (H) and their interaction (H•F) on the exerted force direction, the net shoulder ($M_{shoulder}$) and the net L5/S1 torque ($M_{L5/S1}$).

	Variable	Factor	d.f.	*F*	*p*
Pushing	direction	handle height	2	443.76	< 0.001
		force level	2	147.66	< 0.001
		H•F	4	9.26	0.027
	$M_{shoulder}$	handle height	2	5.82	0.039
		force level	2	30.17	0.001
		H•F	4	0.67	n.s.
	$M_{L5/S1}$	handle height	2	1.00	n.s.
		force level	2	5.37	0.046
		H•F	4	2.57	n.s.
Pulling	direction	handle height	2	8.81	0.016
		force level	2	7.08	0.026
		H•F	4	2.77	n.s.
	$M_{shoulder}$	handle height	2	23.62	0.001
		force level	2	39.27	< 0.001
		H•F	4	7.62	0.037
	$M_{L5/S1}$	handle height	2	54.45	< 0.001
		force level	2	21.56	0.002
		H•F	4	2.36	n.s.

n.s., Not significant.

three force levels). An increased horizontal force from the lowest to the highest target level lead to an increase of the torque from 61 to 127 Nm (averaged over the three heights).

3.4. *Stationary bar versus moveable cart*

The results obtained from the trials with the stationary bar and the trials with the moveable cart were highly comparable. The analysis of variance showed no significant effects of bar versus cart usage on the force direction and shoulder and L5/S1 torque. The bar-cart correlations (*r*) across conditions for force direction ranged from 0.90 to 0.98 among subjects. For the net shoulder and L5/S1 torque these ranges were 0.76 – 0.99 and 0.81 – 0.99 respectively. All correlations were significant.

4. Discussion

4.1. *Force exertion and physical loads*

The direction of force exertion in pushing and pulling was highly reproducible over trials and showed little variation in time during walking. Also, the intersubject variation was small. The directions of the pushing or pulling forces (and its magnitude) on a stationary bar and a wheeled cart were very similar. The direction of force exertion was clearly affected by the horizontal force level and handle height.

The exerted force was more in line with the horizontal at higher horizontal force levels and higher handle heights. This was more pronounced in pushing than in pulling. In pulling, the direction varied from slightly upward pulling to pulling almost horizontally. In pushing, the direction changed from downward

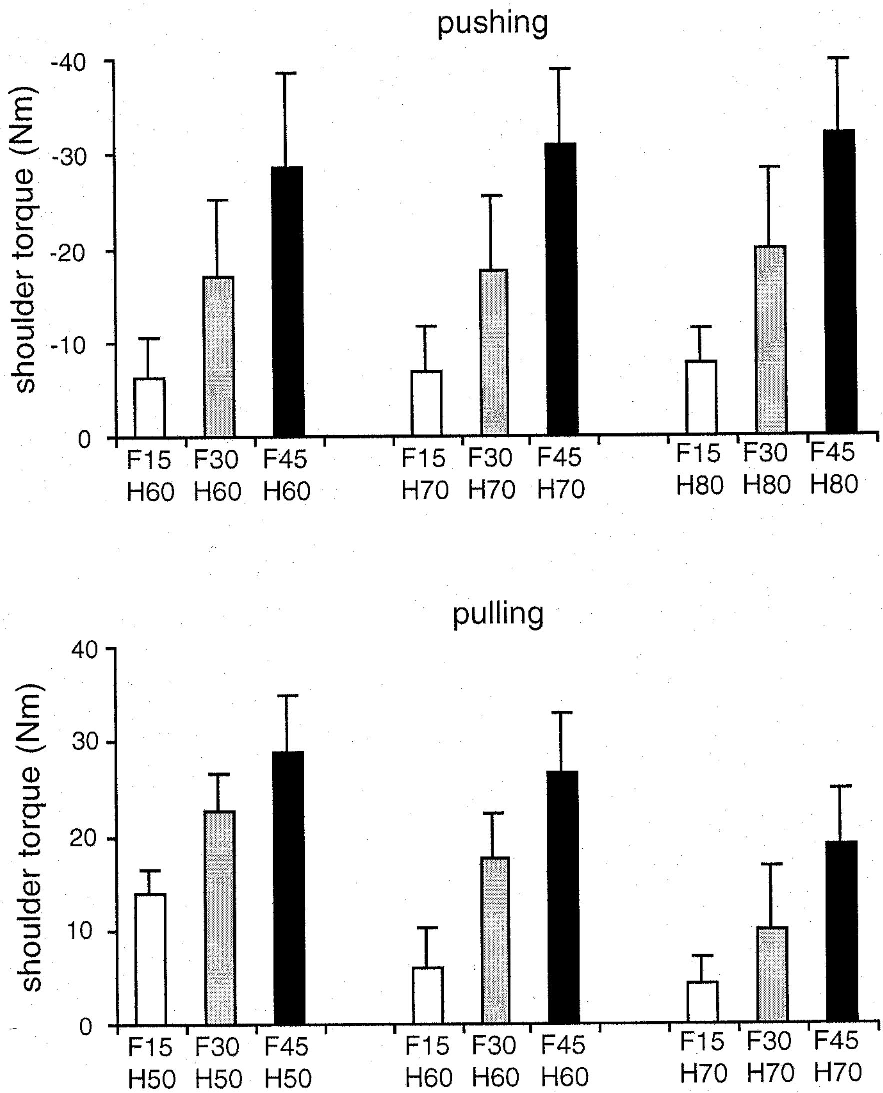

Figure 4. Means and SD of the net shoulder torque in pushing against and pulling on the stationary bar in the various force level (F) and handle height (H) conditions. A positive torque indicates that the task has the effect of rotating the arms backwards.

to near-horizontally pushing, which agrees with Abel and Frank's (1991) results when studying the pushing of a wheelchair at low force levels. Pheasant *et al.* (1982) found for maximal static pushing a change in direction from downward to upward pushing for increasing handle heights from 0.25 to 1.75 m.

The more horizontal direction at increasing handle heights implies that a lesser amount of total force exertion is required to generate the target horizontal force level. In other words, the vertical force component decreases while the horizontal component remains constant at increasing handle heights. Similarly, the more horizontal direction at increasing horizontal force levels (at

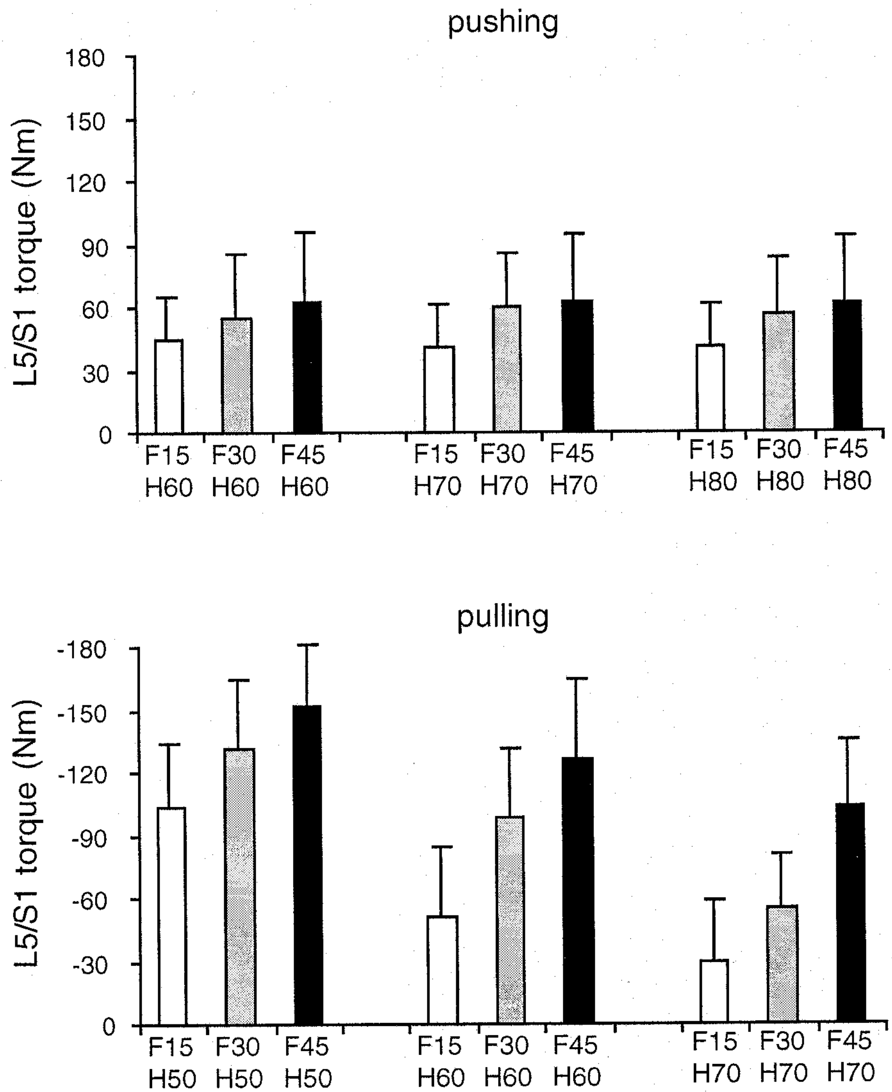

Figure 5. Means and SD of the net L5S1 torque in pushing against and pulling on the stationary bar in the various force level (F) and handle height (H) conditions. A positive torque indicates that the task has a trunk-extending effect.

a given handle height) implies a smaller increase of the total force exertion than would be expected from the rise in horizontal force level. In pushing, the mean decrease in total force exertion from the lowest to highest handle height was 36 N (= 22%), 26 N (10%) and 7.4 N (2%) at the low, middle and high horizontal force levels. A tripling of the horizontal force level in pushing yielded increases in the total force exertion of 2.2, 2.5 and 2.8 times for the three handle heights. In pulling, due to the small variation in force direction, these effects were small.

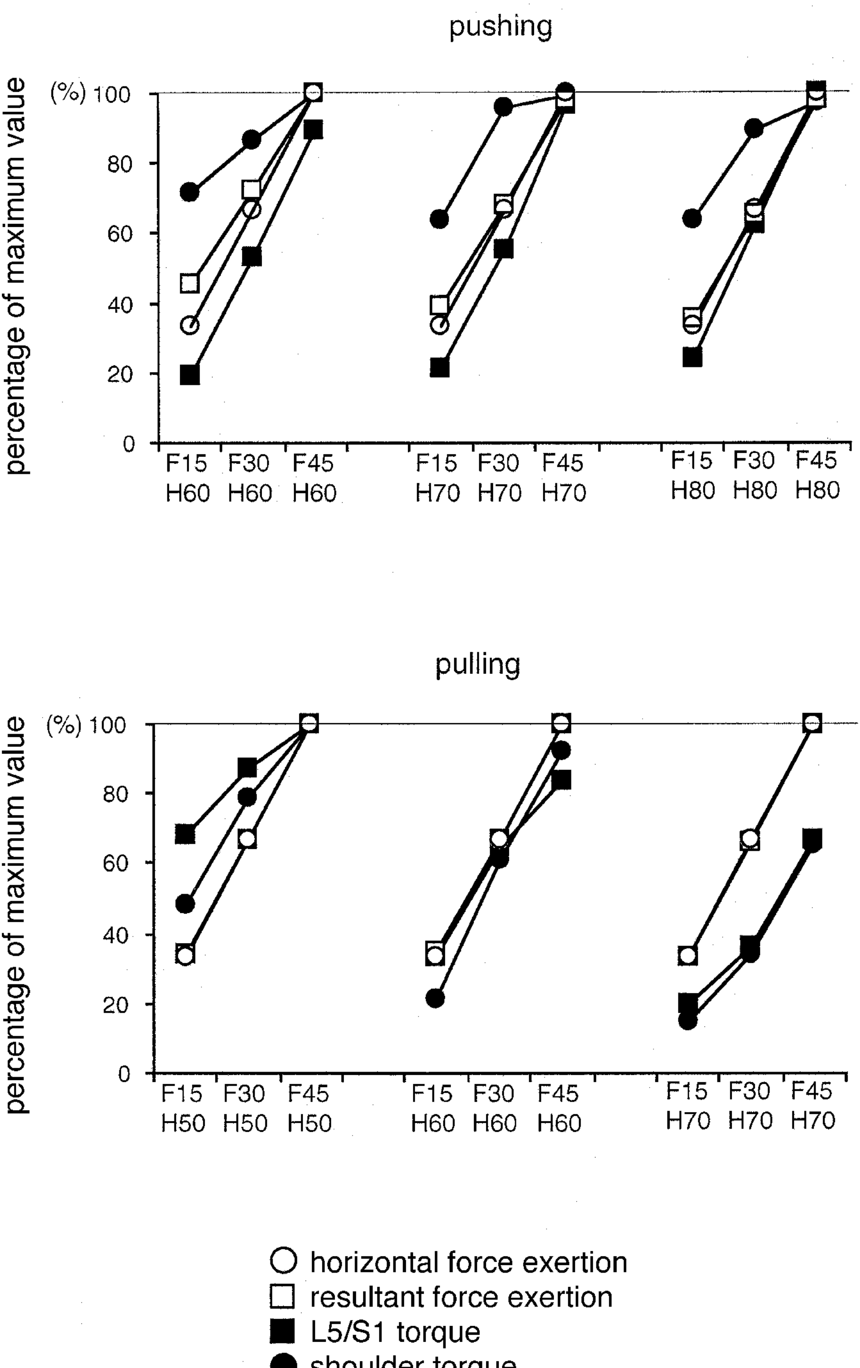

Figure 6. Variations in horizontal force level, resultant force exerted, net shoulder torque and net L5/S1 torque, expressed as a percentage of their highest values observed across force level (F) and handle height (H) conditions.

4.2. *Physical load*

The shoulder and low back load in terms of net joint moment can be seen as a result of the force magnitude and direction with respect to the joint positions and of the posture of the upper body.

For the shoulder, torque values (all <32 Nm) were observed that were hardly affected by the height of the handles and moderately affected by the horizontal force levels. These results can be explained by the line of action running both in pushing and pulling slightly below the shoulder rotation axis irrespective of the handle height and force level, and by the increase in total force exertion at increasing horizontal force levels.

In pushing, relatively small low back torques (all positive and <62 Nm) were found that were significantly, but to a minor extent, affected by force level. Obviously, in all conditions the L5/S1 torque, applied by the reactive force to pushing, is for the most part neutralized by the torque due to the gravity vector applying on the inclined upper body.

In pulling, the reactive force to pulling and the gravity on the upper body also apply opposing torques. However, the torque due to gravity is much smaller as the backward inclination of the trunk is only limited as compared with the forward trunk inclination in pushing. Therefore, the absolute L5/S1 torques are much higher in pulling as compared with pushing, which is in line with previous observations (Lee *et al*. 1991, de Looze *et al*. 1995). Also, a higher handle height favourably affected the low back load, as it reduces trunk flexion and its resultant L5/S1 torque. The horizontal force level in pulling also shows a clear effect on the L5/S1 torque, which is in contrast to pushing (for the higher force exertion is only slightly neutralized by a more backwardly inclined trunk in pulling). With respect to the underlying principles of directing the exerted force, one could conclude from these observations that a strategy to minimize energetic and mechanical loads by minimizing net joints is apparent for the shoulder both in pushing and in pulling, and for the low back only in pushing.

A limitation of this study is its concern with net joint torques only, and not with internal forces. A net joint torque determining the muscle activity minimally required at a joint (to generate the torque) gives an indication of the joint load, but it could be further increased by muscle force required to stabilize the joint and by the non-muscular joint loading directly due to external forces. The stabilizing forces of the shoulder and lumbar spine, however, are likely to be much lower than the forces involved in generating the torque, as the upper extremities are fixed to the bar. The non-muscular joint loading forces would be relatively more important at low torque levels. In the case of pushing, it can be speculated that the low back might be in more danger than would be expected from the low L5/S1 torques: when less trunk-extending muscle forces are required to generate the L5/S1 torque, the spinal stability becomes less (Cholewicki and McGill 1996). Specifically in that case, the high shear forces, due to the reactive force to pushing at the hands, might increase the risk of translocation of spinal tissues (Schibye *et al*. 1997).

4.3. *Practical implications*

The results were obtained from the trials with the stationary bar. These were assumed to resemble cart pushing or pulling, since force exertion and body posture were highly comparable. It should be noted, however, that the cart was moved on an optimal, flat and horizontal surface. Also, only sustained pushing and pulling were investigated, while no attention was paid to the initial phase of accelerating objects. Nonetheless, for sustained pushing and pulling, some practical implications can be formulated.

First, it is of practical value to know to what extent the load on the shoulder and low back are reflected by the total or horizontal amount of force exertion. Figure 6, summarizing the data, shows that the variation in force exertion across conditions roughly agrees with the variation across conditions in shoulder and low back load. As the force exertion rises, the physical load parameters also rise. However, the variation in the force exertion is frequently accompanied by a variation in the other parameters of a lower magnitude. This is particularly true for the shoulder load in pushing and low back load in pulling.

Second, this study shows that the above discrepancies between variations in force exertion and physical load can be traced to variations in force direction. Therefore, for an accurate assessment of physical loads, which may be required for instance in the evaluation of technical ergonomic interventions, one should measure, beside force magnitude, also the force direction with respect to the body posture.

Third, this study adds to the existing literature (e.g. Resnick and Chaffin 1995, van der Woude *et al*. 1995) on the quantification of the effects of handle height and horizontal force requirement on the physical loads on the shoulder and low back, which may help in (re-)designing pushing or pulling working tasks.

Finally, it was found that handle height clearly affects the direction of force exertion, which influences the shoulder and low back load. Thus, this study underlines the need for different guidelines in terms of maximal acceptable pushing or pulling force to be formulated for different handle heights, as has been done before by Snook and Ciriello (1991) and Mital *et al*. (1993).

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